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STUDY OF NASA AND NACA SINGLE-STAGE AXIAL FLOW TURBINE PERFORMANCE AS RELATED TO REYNOLDS NUMBER AND GEOMETRY

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ABSTRACT

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This paper presents the results of a study conducted in two parts based on results of NASA and NACA single-stage turbine investigations. The first part was a survey of experimental turbine investigations that were conducted over a range of Reynolds numbers, and the second part was a study of turbine loss as related to geometry. In the first part of the study the turbines investigated covered a range of Reynolds numbers from 10^4 to 2×10^6, where Reynolds number is defined as the ratio of weight flow to the product of viscosity and rotor radius at the mean section of the blades. In this phase of the study an attempt was made to correlate a basic turbine loss parameter with Reynolds number with the result being that a correlation could not be made. One of these turbines, however, did show a large change in performance with Reynolds number. A second study of turbine loss as related to geometry was then made. For this part of the study, data from additional turbine investigations were used. As a result, the stator throat area seemed to correlate with the loss parameter for the majority of the turbines investigated. An expression was obtained that related the loss parameter with the stator throat area.

INTRODUCTION

The NASA and former NACA have on occasion during the past years conducted experimental investigations of the effects of Reynolds on turbine performance characteristics. The turbines used for these investigations covered a broad range of types as a result of the changing interests of the Agency. The turbines investigated included those that had applications in the areas of supercharger drives, turbojet engines, rocket propellant-pump drives, and auxiliary power systems (refs. 1 to 9). Although the range of Reynolds numbers covered for each turbine did not vary ~~more~~ than approximately one order of magnitude, the total range when considering all the turbines varied from 10^4 to 2×10^6. Reynolds number is defined herein as the ratio of weight flow to the product of viscosity and rotor radius at mean section of the blades. Included in the paper is a brief description of the turbines and their performance over a range of Reynolds numbers covered in the individual investigations. Also included are the results of a loss calculation conducted in order to present the results of those turbine investigations in terms of a loss parameter. The use of this loss parameter is intended to eliminate differences in velocity diagrams and types of efficiencies of the various turbines, thereby providing a common basis for comparison.

The results of the Reynolds number study were used as a basis for the second part of the study. This phase of the study included 10 additional turbines (refs. 11 to 17) and was made in order to determine if a size parameter could be established that would be related to turbine loss. These results are also presented.

REYNOLDS NUMBER STUDY

NASA Turbine Programs

As mentioned in the INTRODUCTION, the results of 10 turbine performance evaluations related to Reynolds number will be discussed. The results of these investigations are presented in figure 1, where the turbine efficiencies (as taken from their respective reports) are plotted versus Reynolds number. Reynolds number will be defined here as

$$Re = \frac{W}{\mu r_m}$$

where

W is the turbine weight flow

μ is the gas viscosity at the turbine inlet total conditions

r_m is the radius of the rotor at the mean section of the blades

A derivation of this Reynolds number is found in reference 10.

Included in the following paragraphs will be a brief description of the turbines and a summary of the results of each investigation, as reported.

Turbine I (ref. 1) was a single-stage transonic turbine with a tip diameter of 7 inches. This turbine was designed to have zero suction surface diffusion on the rotor blades. The investigation was made at two different inlet total pressures, and thus two different Reynolds numbers; and the results showed no change in performance as a result of the different Reynolds numbers.

Turbine II (ref. 2) was a single-stage turbine with a downstream stator. The turbine tip diameter was 15 inches. This turbine was tested at three different inlet total pressures and did show a decrease in performance with decreasing Reynolds number.

Turbine III (ref. 3) was an impulse-type turbine having a 12-inch tip diameter. This turbine was tested over a range of inlet total pressures and at two different inlet total temperatures. The results showed a variation in performance over the range of conditions investigated. The stator blades of this turbine were bent sheet metal vanes having no airfoil shape.

Turbine IV (ref. 4) was the same turbine as turbine III except that the stator blades were replaced with airfoil shaped blades. This investigation was conducted at only one Reynolds number but is included here because it indicates what the performance of turbine III would have been with airfoil shaped blades.

Turbine V (ref. 5) was an impulse-type turbine having a tip diameter of $14\frac{3}{4}$ inches. This turbine was also operated over a range of inlet total pressures and at two inlet total temperatures. The results obtained with this turbine showed an effect of Reynolds number on the performance.

Turbine VI (ref. 6) was a 4-inch tip diameter turbine that was operated over a range of inlet total pressures. The results from this investigation indicate a considerable effect of Reynolds number on turbine performance.

Turbine VII (ref. 7) was a transonic turbine exactly the same as turbine I except that its diameter was twice that of turbine I. This turbine was operated at one half the inlet total pressure of the high Reynolds number point of turbine I. The efficiency of this turbine was approximately 2 percent higher than the efficiency of turbine I.

Turbines VIIIA and B (ref. 8) were two similar single stage turbines, each being operated in hydrogen and nitrogen gas, thereby effecting operation at different Reynolds numbers. The performance results are not presented here or in figure 1 because of a security classification of the report; however, it can be reported here that the performance was not affected with changing Reynolds number.

Turbine IX (ref. 9) is a turbine that was also operated in two gases (hydrogen and nitrogen) and, as for turbines VIIIA and B, the performance results are classified. Again the performance was not affected by changing Reynolds number.

Turbine Performance on a Loss Basis

In the preceding pages a discussion of the results of 10 turbines investigated was presented showing the effect of Reynolds number on the turbine performance as indicated by overall efficiency. As pointed out previously, these results were shown as they were taken from their respective reports. Because these turbines have various design features and different types of velocity diagrams and because different types of efficiencies are used, they cannot be directly compared on an efficiency basis such as that shown in figure 1. Since Reynolds number is basically a parameter that effects blade loss, it appears that if a correlation is to be made it should be made using a loss term. Reference 10 presents a method of relating velocity diagram parameter to turbine efficiency using such a loss term.

In this paper the same basic equations of reference 10 are used, except the loss parameter (which will be referred by the symbol L) is unknown and will be computed from the efficiency and velocity diagram parameters.

Loss parameters were computed for the turbines presented (refs. 1 to 9) and are plotted in figure 2 as a function of Reynolds number. In computing the value of the loss parameter for turbine II (single stage with downstream stator), the performance of just the first stage was used, thereby eliminating any effects caused by the downstream stator blade (which is of compressor blade design). It may be seen then that the performance was not affected by Reynolds number when considering just the first stage. Turbines A and B of reference 8 and the turbine of reference 9 are now shown.

Three observations can be made from the figure. They are (1) for Reynolds number below approximately 2×10^5 there is a variation in the loss parameter with Reynolds number, (2) for values of Reynolds number above approximately 2×10^5 there appears to be no variation of the loss parameter with Reynolds number, and (3) there is a variation of the loss parameter between different turbines at the same values of Reynolds number.

From these observations it is concluded that there are other factors besides Reynolds number that are predominant in influencing the loss parameter for the various turbines and that there appears to be an effect of Reynolds numbers on the loss parameter for turbines that were operated at Reynolds numbers below approximately 2×10^5. One investigation that was conducted at the lowest values of Reynolds number to date did show a considerable effect of Reynolds number on its performance.

In summary then, the conclusion drawn from the results of the loss study of these 10 turbines is that no correlation appears to exist between the turbine losses and Reynolds number. Therefore, since a correlation does not seem to exist with Reynolds number, and there is a variation of losses between the different turbines, it appears that there are other factors that must influence the performance of turbines.

Loss Study as Related to Turbine Geometry

In the preceding section it was determined that a correlation did not exist between the turbine loss parameter and Reynolds number and that there must be other factors that influence the variation of the loss parameter for the various turbines. These factors may include such items as tip clearance loss, trailing-edge blockage, accuracy of fabrication of blade shape and blade surface finish. Therefore, a study was made using various parameters involving turbine geometry to try to correlate with the turbine loss parameter. One parameter that appeared to correlate the turbine loss parameter better than others was the stator throat area. Other parameters considered were specific diameter, blade height, blade chord, tip diameter, and solidity.

Since this part of the study is now concerned with turbine geometry, ten more turbines were included in addition to the previously described ten turbines. All of these additional turbines were single-stage units or the first stage of multistage units. A detailed description of these turbines will not be presented here because of the number involved, but a complete description will be found in their respective reports (refs. 11 to 17). A brief description of these turbines follows:

Turbine XI was the first stage of the J73 turbojet engine turbine. Turbine XII was a reduced chord version of turbine XI having the same solidity as turbine XI. Turbines XIII, XIV, and XV were all 14-inch-tip-diameter turbines that were part of an investigation to optimize solidity and turbine rotor total diffusion. Of these three units, turbine XV had optimum solidity and zero suction surface diffusion on the rotor and had the highest efficiency of the three. Turbine XVI was a first stage of a three-stage turbine and was designed by using the results of calculated velocity distributions on the blade surfaces. Turbines XVIIA to D were a series of small turbines which were of similar design but had varying blade heights. Turbines XVIIA to D were not NASA turbines but were used because of the extremely small stator throat areas. The blade heights of these turbines were 0.2, 0.1, 0.04, and 0.020 inch. All of these turbines were made with a 4.0-inch tip diameter.

Of the 20 turbines presented, 10 of these were designed using rigorous analyses for flow continuity through the turbine and for velocity distributions on the blade surfaces. These 10 turbines are numbers I, II, VII, VIIIA, VIIB, IX, XIII, XIV, XV, and XVI.

Loss parameters were computed for all turbines presented, and these values are plotted in figure 3 as a function of the stator throat area. A straight line is shown drawn through the lowest of these points; the equation for this line is $L = 0.0384\, A_{th}^{-0.165}$. The turbines whose values of loss parameter fall along this line have either or both of the following features: (1) high efficiency (2) designs made in accordance with minimum rotor blade tip loss, minimum trailing-edge blockage, total diffusion between 0.4 and 0.5, and near zero rotor suction surface diffusion. Figure 3 also shows data points appearing above this line, that is, in the higher loss region. These points represent turbines designed without rigorous analysis of velocity distribution on the blading. Thus, it may be concluded that these turbines could have had smaller losses had a more comprehensive procedure been used in the design of the blading.

Turbines XVIIB to D also fall above this line. These data suggest that the curve be drawn to curve upward in the region of small stator throat area, but more data are needed in this region in order to establish such a curve. Thus, it appears that the stator throat area correlates with the turbine loss parameter. Since an expression was obtained for the loss parameter in terms of the stator throat area, it is suggested that this expression be substituted for the loss term $K(Re)^{-1/5}$ in the equation of reference 10.

Concluding Remarks

This paper has presented the results of a study of Reynolds number effects on turbine performance and the results of a study of turbine geometry as related to turbine performance. The results of the Reynolds number study are:

1. For values of Reynolds number below approximately 2×10^5 there is an effect of Reynolds number on turbine performance.

2. For values of Reynolds number above approximately 2×10^5 the Reynolds number effects were negligible.

3. There was a difference in the loss parameter for various turbines at the same values of Reynolds number.

It was concluded that, for the turbines covered by this study, a correlation of turbine loss with Reynolds number did not appear to exist and a reasonable correlation of the turbine loss parameter with stator throat did exist. The variation of turbine loss parameter with stator throat area was $L = 0.0384 \, A_{th}^{-0.165}$

NOMENCLATURE

A_{th} stator throat area, sq in.

K constant of proportionality

L turbine loss parameter (This term corresponds to the parameter $K(Re)^{-1/5}$ as used in ref. 10)

n exponential term of Reynolds number

Re Reynolds number

r_m radius of rotor at mean section of blade

W weight flow, lb/sec

μ gas viscosity, lb/ft-sec

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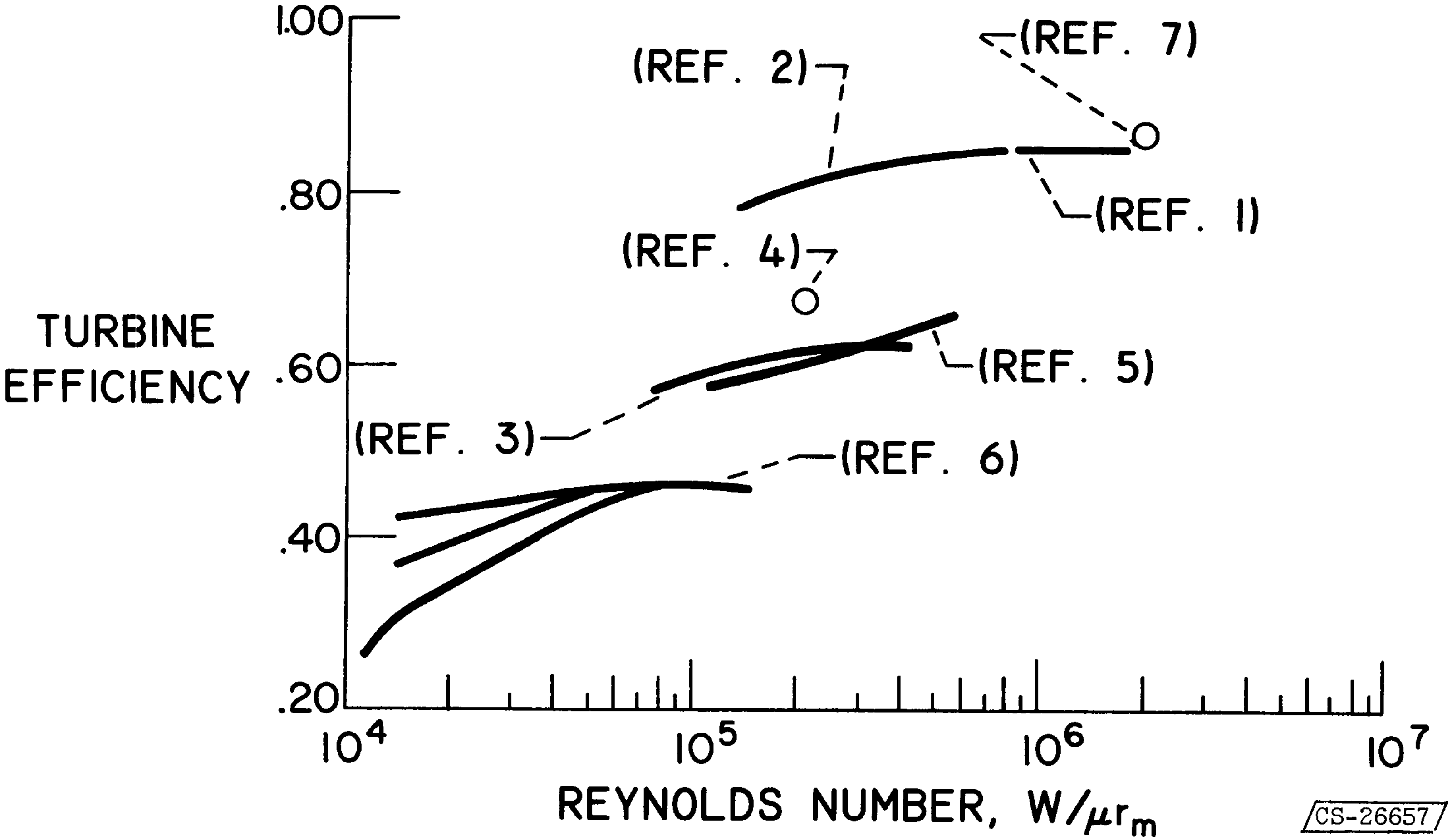

Figure 1. - Variation of turbine efficiency as reported with Reynolds number.

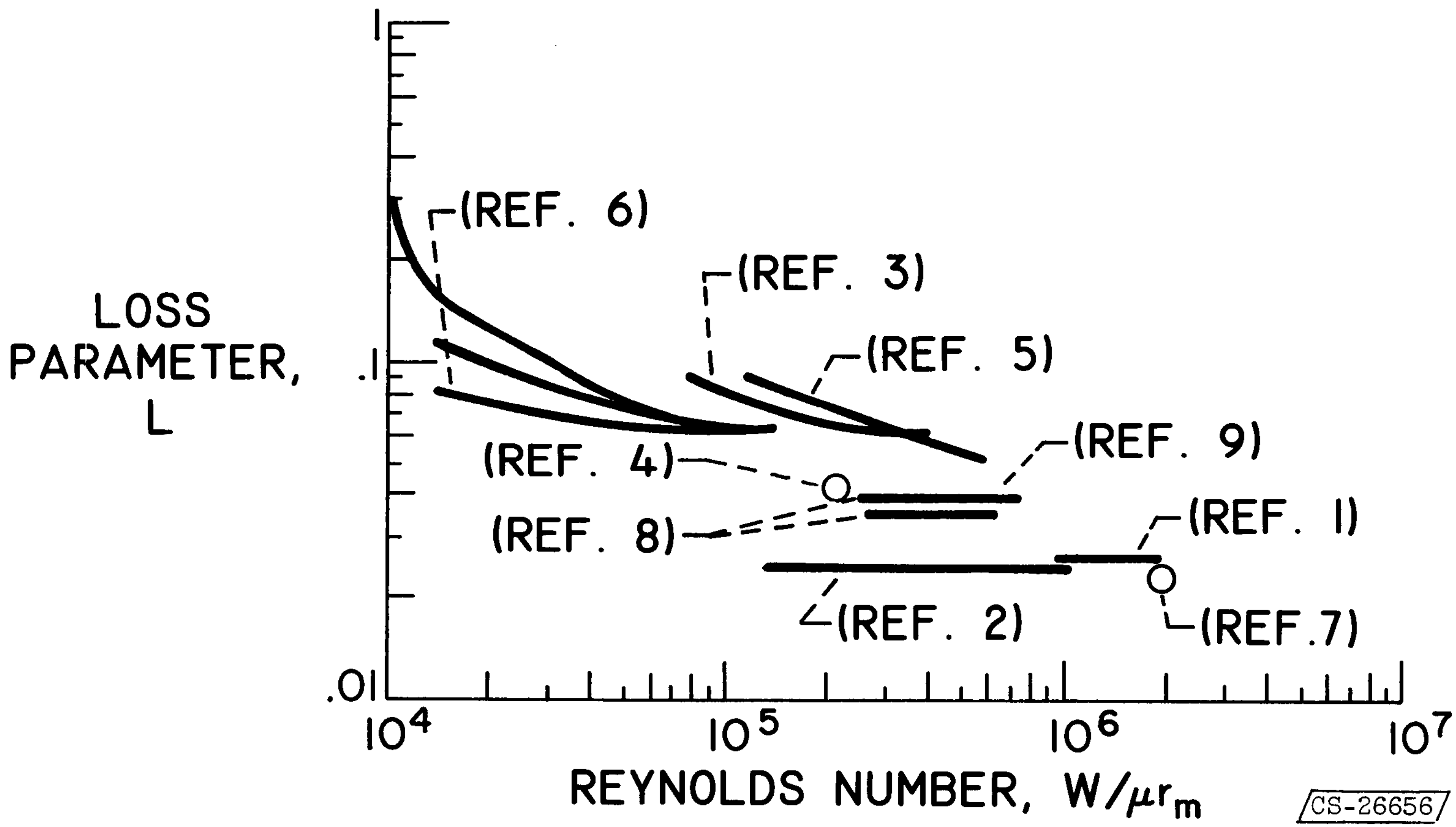

Figure 2. - Variation of loss parameter with Reynolds number.

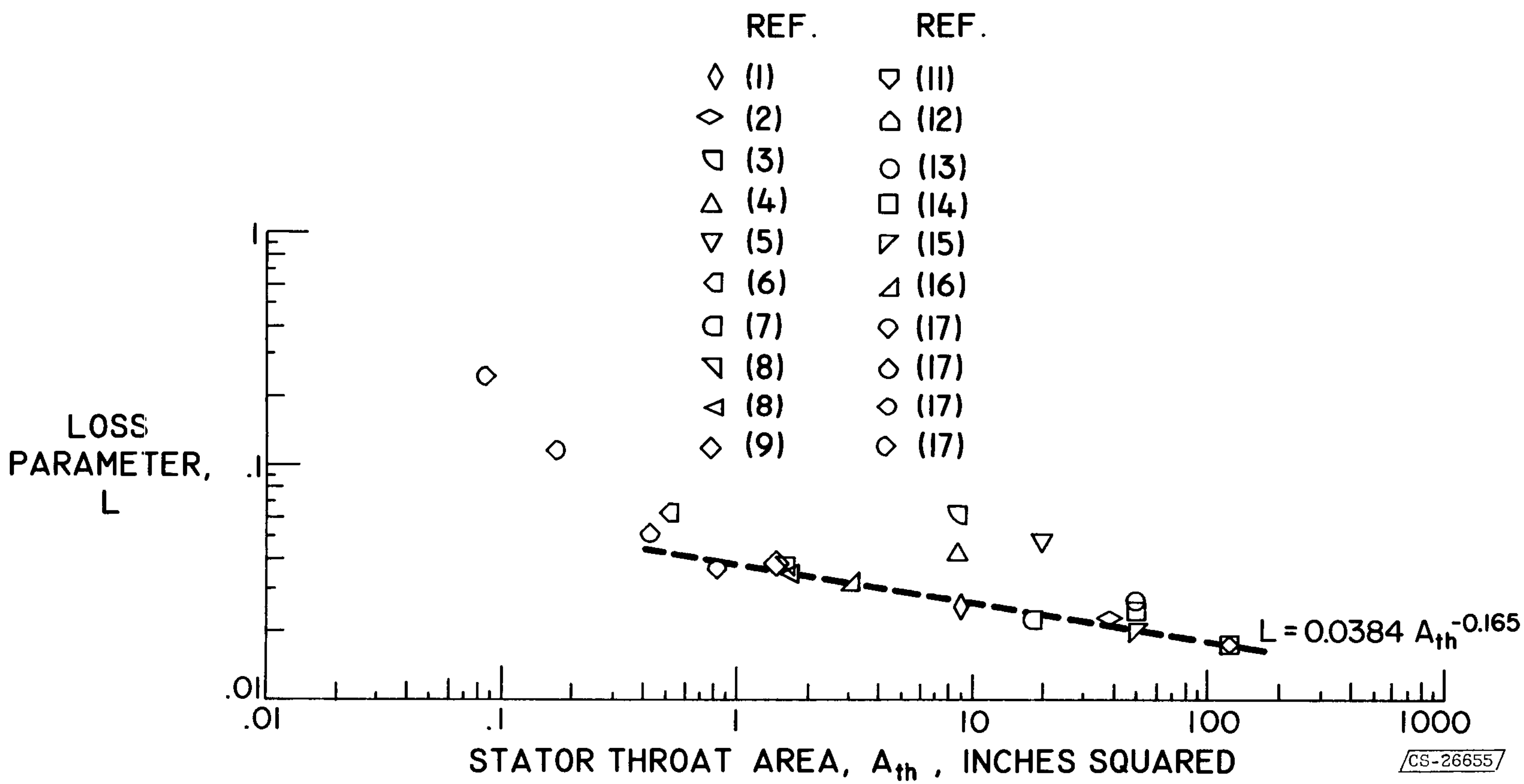

Figure 3. - Variation of loss parameter with stator throat area.